AD-A132 194   ESTABLISHMENT OF WEARMETAL GUIDELINES FOR ARMY GROUND   1/1
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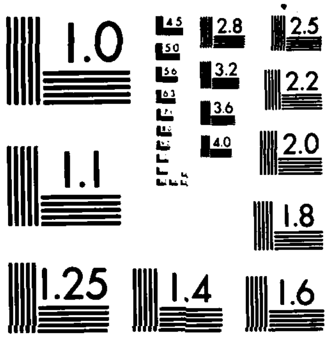

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THESIS

ESTABLISHMENT OF WEARMETAL GUIDELINES
FOR ARMY GROUND EQUIPMENT

by

Richard Frank Bauer

June 1983

Thesis Advisor: Harold J. Larson

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A132 194	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Establishment of Wearmetal Guidelines for Army Ground Equipment		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis June 1983
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard Frank Bauer		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, Ca 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, Ca 93940		12. REPORT DATE June 1983
		13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Spectrometry; Oil Analysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Establishment of Wearmetal Guidelines for Army Ground Equipment

by

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Captain, United States Army
B.S., Cornell University, 1974

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This thesis utilizes historical wearmetal data from the Ft. Ord Spectrometric Oil Analysis laboratory to propose wearmetal level and trend guidelines for equipment powered by the Continental LD/LDS/LDT 465/465-1 engine. The methodology proposed for determining trend guidelines requires data giving the parts-per-million (PPM) level of a given wearmetal at a known time since oil change.

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I. INTRODUCTION

During the operation of any piece of mechanical equipment, a certain amount of abrasion occurs between metal parts coming in contact with one another. The result of this abrasion is the deposition of minute quantities of metal (wearmetals) in the lubricating oil of the equipment.

It was recognized by the railroads as far back as the 1940's that monitoring the concentration of wearmetals in the lubricating oil could be useful in determining the mechanical condition of diesel engines and forewarn the breakdown of engine components.

Later in the mid 1950's, the Navy began a trial monitoring program at the Naval Air Rework Facility in Pensacola to determine if oil analysis techniques could be useful for detecting the abnormal operation of aircraft engines. Following the success of the Navy effort, the Army first applied the techniques to the monitoring of reciprocating engine helicopters in 1959. An evaluation of oil analysis programs was initiated by the Air Force in 1962 and resulted in the establishment of an Air Force oil analysis testing program in 1964.

Consolidation of Department of Defense oil analysis programs was initiated in 1969 with the DOD Equipment Oil Analysis Program (EOAP) and later the Joint Oil Analysis Program (JOAP). The purposes of this consolidation were to effect uniformity and standardization in oil analysis program equipment, standards and techniques, consolidation of procurement requirements for oil analysis equipment and the centralization of responsibility for technical management and overall program surveillance.

The basic assumptions of the spectrometric analysis of wearmetals is that during the normal operation of a piece of equipment, the interacting of parts results in the production of minute quantities of metals. This wearmetal production occurs at a constant rate (as a function of time) for properly operating pieces of equipment. However, as a part enters into its failure mode, a much higher level of wearmetal particles may be deposited into the lubricating oil. An illustration of this process for a hypothetical piece of equipment is shown in Figure 1.1.

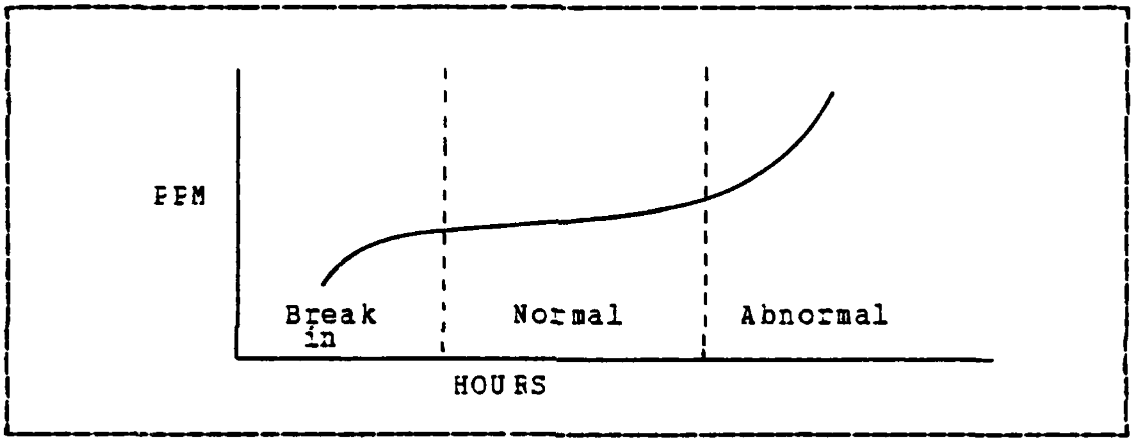


Figure 1.1 Hypothetical Wearmetal Production.

There are limitations to the types of failure which can be identified through spectrometric analysis. The types of failure which can be detected are failures which are accompanied by wearmetal production and which occur at a slow enough rate to allow maintenance action after identification of a possible failure. Some of the types of unidentifiable failure are:

1) failures which produce large wearmetal particles visible to the naked eye

2) failures which occur too rapidly to be detected by the current oil analysis procedures
3) failures which occur without appreciable production of wearmetals

To identify impending failure conditions, wearmetal levels in an oil sample from the equipment studied are determined through spectrometric analysis. Next, the laboratory personnel calculate a 10 hour PPM increase figure by finding the change in PPM between samples, dividing that figure by the hours between samples (giving a rate of increase per hour) and multiplying by 10 (giving the rate of increase for 10 hours). A guideline chart giving wearmetal PPM criteria for normal, marginal, high and abnormal ranges and for abnormal 10 hour trends is consulted for the applicable type of equipment. These guidelines are not recommended wearmetal values, but indicate ranges of values within which the PPM levels of similar equipment have historically fallen.

A determination is made as to whether the amount of wearmetals in the sample is considered in the normal, marginal, high, or abnormal range and whether the PPM increase in the 10 hour period is abnormal. Based on the range of the sample, the range of the previous sample, the trend reading and whether the oil sample was a routine submission or the result of a laboratory request, a recommendation is made utilizing the Decision Making Guidance Table (Table 6-1) of TM 38-301. Basically the table calls for increased sampling if there is an indication of abnormal operations. Continued abnormal readings result in the deadlining of the equipment and a recommendation that maintenance action be initiated to determine the cause of the high level of wearmetals. In some cases a combination of abnormal wearmetal readings can be used to pinpoint the

specific area of the equipment which is probably in the process of failing.

The maintenance personnel must then provide followup to the oil analysis laboratory stating whether their indication of impending failure was correct (known as a 'hit') or incorrect (known as a 'miss').

Thus, through the combined efforts of the oil analysis laboratory and the maintenance personnel, many impending failures can be detected and corrected, preventing further damage (or perhaps destruction) of the equipment and serious injury to the personnel operating it.

II. NATURE OF THE PROBLEM

Extension of the oil analysis program to Army non-aeronautical equipment is fairly recent, therefore there are a number of engines in the Army inventory which are still lacking wearmetal and trend guidelines. The DARCOM Materiel Readiness Support Activity at Lexington, Ky. provided a list of engines, used in Army ground equipment, which were lacking published guidelines. Of the engines listed, the one which was most widely used (in terms of types of equipment of different nomenclature) was the Continental LD/LDS/LDT 465/465-1 (henceforth referred to as the LDS-465). This is a six cylinder diesel engine which powers a large number of the Army's 2 1/2 Ton and 5 Ton trucks. A list of the types of vehicles powered by the engine is at Appendix A.

The goal of the analysis was to examine historical data (from DD Form 2027- Oil Analysis Record) on a large sample of different vehicles operated in different parts of the country, which were equipped with the LDS-465 engine. From this analysis it was hoped to derive guidelines for what could be considered normal, marginal, high and abnormal concentrations of wearmetals in the lubricating oil. These guidelines were to be general (i.e. applicable to all types of equipment using the subject engine) in keeping with the format of the guidelines published in TM 38-301 and TM 38-301-1. In addition, it was desired to determine the relationship between operating hours of the piece of equipment and the rate of wearmetal production. This information was to be used to develop guidelines on what was to be considered an abnormal increase in wearmetal PPM over a 10 hour operating period.

Due to time constraints in conducting the analysis, Army wide data could not be obtained. The scope of the analysis was therefore limited to a sample of data on equipment serviced by the Ft. Ord Spectrometric Oil Analysis Laboratory. This limitation on the scope of the analysis also placed a limitation on the applicability of the results in that they are only representative of the equipment at Ft. Ord and are based on a relatively small sample, thus extension of the results to Army wide equipment should be avoided. The methodology, however, may be useful in analyzing a much larger set of data in order to provide guidelines applicable to Army wide equipment.

III. ANALYSIS METHODOLOGY

A. DATA COLLECTION

Historical oil analysis records (DD Form 2027) for the period January 1980 through January 1983 were examined for 76 vehicles from Active Army units located at Ft. Ord. The records studied were for 2 1/2 Ton Cargo trucks of the type M35A2 or M35A2C. A list of serial numbers for the vehicles examined is at Appendix B.

The M35A2 and M35A2C are tactical vehicles and as such, the guidance on routine sampling intervals is once every two months. Samples are taken while the oil is warm either by the use of a dip tube or by a drain outlet. Detailed descriptions of the sampling methods are found in TM 38-301 or TB 43-0211.

An Oil Analysis Request (DD Form 2026) is filled out giving such information as equipment identification data, time oil sample taken and method used (drain or dip tube), hours since oil change, hours since overhaul, and any statements about unusual operation of the equipment. The samples are then sent to the Oil Analysis Laboratory at Ft. Ord where a spectrometric analysis is performed to determine wearmetal levels in the sample.

The analysis is accomplished by the use of the Baird Emission Spectrometer Model A/E35U-3. A small portion of the oil sample is placed in the spectrometer. A carbon disk electrode rotates through the sample, picking up a film of oil which is burned by an electric arc between a fixed electrode and the rotating disk. The energy radiated by the burning oil is separated into its component wavelengths and

the intensity measured. This is compared to the intensity measured from calibration samples to determine the parts per million (PPM) levels of the various wearmetals in the sample. There is a degree of variablility associated with the spectrometer reading. TM 38-301 states the spectrometer has a tolerance of ±1.0 PPM; however it seems more likely the variability is a function of the magnitude of the reading as suggested by the spectrometer manufacturer.

After spectrometric analysis, the following information is then entered into the DD Form 2027 (Oil Analysis Record) for the sampled piece of equipment.

1. Sample number (laboratory assigned)
2. Data index (data correction or maintenance feedback)
3. Julian date sample analyzed
4. Laboratory response time
5. Last laboratory recommendation
6. Hours since overhaul
7. Hours since oil change
8. Reason for the sample
9. Wearmetal levels
10. Post analysis data (lab recommendations and maintenance followup)

None of the records studied indicated laboratory recommendations for maintenance action and thus no reports of maintenance followup existed. It was also found that approximately 25% of the historical records lacked data for hours since oil change and hours since overhaul. This precluded any systematic analysis of the entire sample of

wearmetal levels as a function of operating hours. As a result, to determine wearmetal guidelines, an analysis was conducted which did not require operating hour information.

The suggested oil sampling intervals were also not adhered to in all cases. As a result, the number of records available for each equipment during the time period studied, ranged from 14 to 17 samples.

B. DETERMINATION OF WEARMETAL LEVEL GUIDELINES

Faced with these constraints, the method of analysis chosen was to look at all of the PPM levels available for the 76 vehicles, plot a frequency distribution and examine the quantiles from the empirical distribution.

The director of the Ft. Ord Oil Laboratory provided guidance on the major wearmetals of concern for the LDS-465 engine. They were:

1. Iron (Fe)

2. Aluminum (Al)

3. Chromium (Cr)

4. Copper (Cu)

5. Lead (Pb)

Thus the scope of the study was limited to these five wearmetals. The wearmetal data was read by the FORTRAN program WEARMTL (see Appendix F for computer program listings) which produced an output frequency histogram for each wearmetal along with a number of sample statistics. In all, a total of 1255 sample points were available. The 60th, 70th, 80th, 90th, 95th, 96th, 97th, 98th, and 99th quantiles were determined from the data. No decisions were made on

what labels (i.e. normal, marginal, high, or abnormal) to place on these quantiles, but rather to provide this information to the Oil Analysis Laboratory director for use in his own subjective judgement. The quantiles found are listed in Table I. Output histograms are at Appendix C.

TABLE I

Selected Wearmetal Quantiles

	Quantile								
Wearmetal	60th	70th	80th	90th	95th	96th	97th	98th	99th
Iron	94	108	124	149	175	180	200	215	238
Aluminum	20	25	30	38	46	47	50	53	57
Chromium	9	10	12	15	18	18	19	21	24
Copper	16	19	24	31	38	41	46	51	73
Lead	39	48	61	76	91	95	104	116	137

C. DETERMINATION OF 10 HOUR TREND GUIDELINES

In addition to wearmetal levels, a major concern in the oil analysis program is wearmetal trends. Trend guidelines are established for a standard 10 hour period and give what is considered to be an abnormal increase in wearmetal levels for that period. In the study performed by the ARINC Corporation for the U. S. Air Force [Ref. 1, pp 10-14] the method of piecewise or segmented regression was used to determine the point of onset of failure. In this method, wearmetal concentration data on a number of similar pieces of equipment is divided into two groups, that data representing normal wear and that representing abnormal wear.

The hours associated with each sample are converted from hours since oil change to hours prior to detection of failure. This indicates the necessity of maintenance feedback to determine or verify a point of failure detection. Straight lines are then fit through both sets of data using the procedure detailed by Hudson [Ref. 2]. The point of intersection of the two lines is taken to be the time prior to detection at which failure commenced (see Figure 3.1). The slope of the line following this point could then be used to calculate abnormal 10 hour trends.

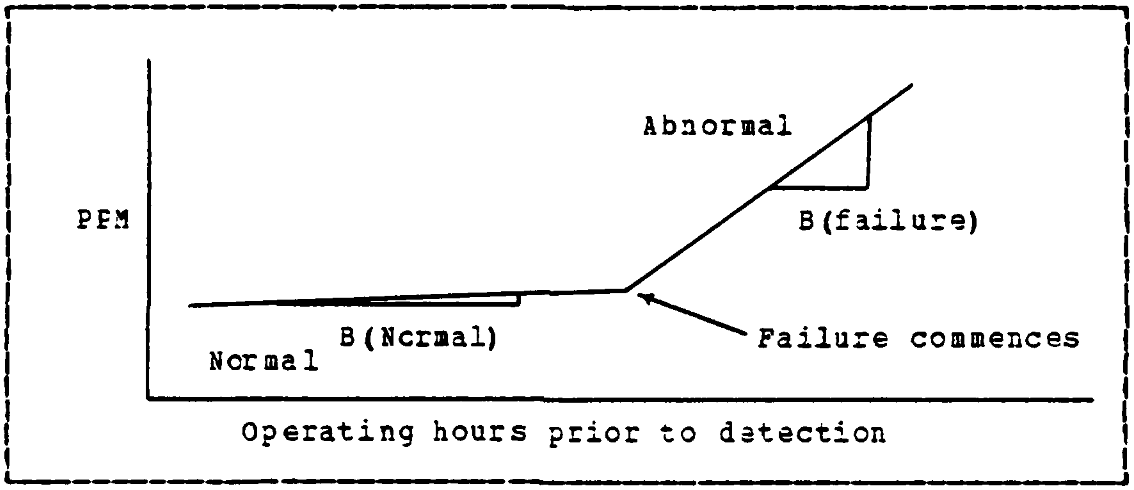


Figure 3.1 Fitting Data By Piecewise Regression.

Since no maintenance feedback was available, a technique was proposed which would indicate abnormally high metal trends without requiring maintenance information on actual failure conditions. This method assumes that:

1. Wearmetal levels may depend on operating hours of the equipment.

2. A possibly different relationship exists for the normal and abnormal periods of operation.

3. The rate of wearmetal production is higher during failure than during normal operation.

Instead of fitting piecewise regression lines to the data, the proposed methodology treats the slope of each line segment (whose end points are formed by successive wearmetal readings) as an estimate of the rate of wearmetal production. An illustration of this technique is given in Figure 3.2. Each dotted line segment provides an estimate of the

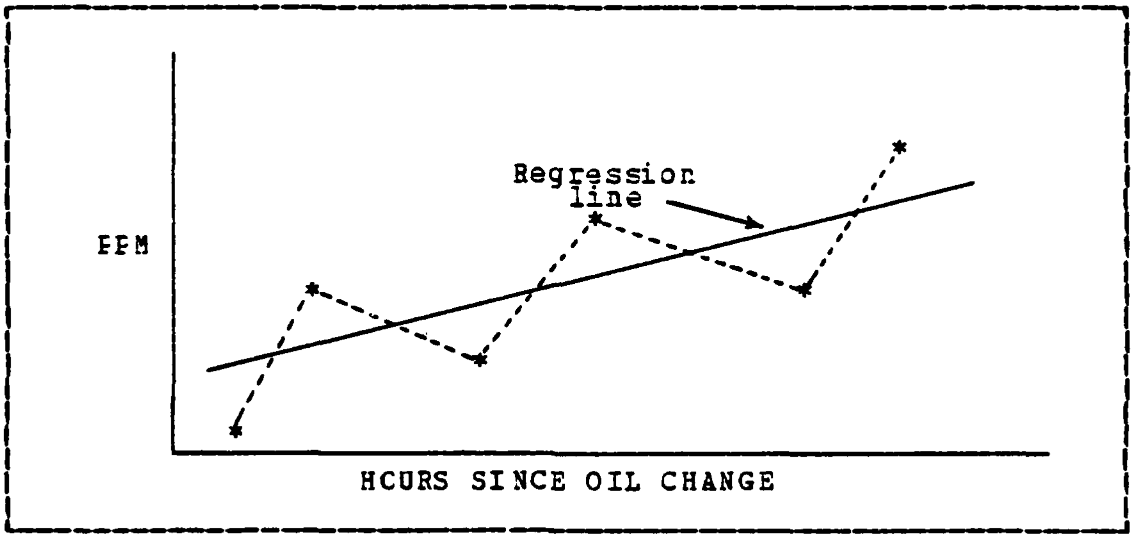


Figure 3.2 Piecewise Estimation 10 Hour Wearmetal Trends.

production rate. If the wearmetal production rate is linear, the relationship is of the form:

$$Y(i) = B(0) + B(1)*X(i) + E(i)$$

Where:

$X(i)$ = hours since oil change for the ith sample

$Y(i)$ = wearmetal reading for the ith sample

$B(0)$ = intercept of the regression line

$B(1)$ = slope of the regression line

$E(i)$ = deviation of the actual wearmetal reading from the regression line.

The above definitions apply throughout the rest of the thesis.

The slope of each successive line segment is found by the formula

$$\text{slope} = (Y(i+1)-Y(i))/(X(i+1)-X(i))$$

substituting the regression equations:

$$\text{slope} = \frac{E(0)+(B(1)*X(i+1))+E(i+1)-B(0)-(B(1)*X(i))-E(i)}{X(i+1)-X(i)}$$

$$=E(1) + (E(i+1)-E(i))/(X(i+1)-X(i))$$

Since the regression slope $B(1)$ is constant for any given set of data, each pairwise slope will deviate from the actual slope by a factor

$$(E(i+1)-E(i))/(X(i+1)-X(i))$$

Thus, the 'goodness' of this method is determined by the magnitude of the variance in the residuals and the length of time between wearmetal samples. Samples with small variances in their error terms and large sampling intervals will approximate the regression slope much better than those with large variances and small sampling intervals.

The next step in the methodology is to convert each of these slopes to a PPM increase for a 10 hour period. This is done by multiplying the slope by 10:

Increase in PPM in 10 hours $= 10*(B(1)+(((E(i+1)-E(i))/(X(i+1)-X(i)))))$

Thus each of the slope segments (regardless of the time interval between the samples) is converted to a change in

PPM which would be expected during any 10 hour period within this interval. The 10 hour PPM rate of change measurements are then grouped together in a frequency histogram. If the rate of wearmetal production is higher during failure than during normal operation, then the upper quantiles of the PPM rate of change distribution should represent those samples from the failure mode of the equipment.

This methodology was applied to the Fort Ord data (for those data elements which had hours since oil change information available) through the use of the FORTRAN program ANALYSIS (Appendix F). The logic used in computing the slopes was:

1. If no hours since oil change data was available, the sample was discarded.
2. If hours since oil change was greater than the previous reading, the slope was determined by:

   (Y(i+1)-Y(i))/(X(i+1)-X(i))

3. If hours since oil change was less than that of the previous sample, it was assumed an oil change took place and thus the slope was calculated by:

   Y(i)/X(i)

Since approximately 25% of the records lacked time since oil change data, only 876 trend values were computed. Histograms of the trend frequencies are at Appendix D. The results obtained showed a large variance in the PPM rate of change levels. This may have been due to errors in data reporting since a large factor in the variance was the existance of a few extremely large or small measurements. As in the case of the wearmetal levels, selected quantiles were obtained and are shown in Table II.

TABLE II

Selected 10 Hour Trend Quantiles

	Quantile								
Wearmetal	60th	70th	80th	90th	95th	96th	97th	98th	99th
Iron	6.0	9.3	15.7	31.9	66.9	86.3	140.	190.	230.
Aluminum	1.2	2.0	3.5	8.5	20.0	23.8	30.0	41.3	70.0
Copper	1.1	1.9	3.3	7.5	15.9	20.9	26.9	35.0	45.9
Chromium	0.5	0.9	1.5	3.3	8.0	10.0	13.0	20.0	23.3
Lead	2.4	4.5	8.8	18.3	37.5	42.4	52.5	80.0	110.

IV. ILLUSTRATION OF TREND ANALYSIS TECHNIQUES USING SIMULATED DATA

The technique proposed for analyzing trends was not adequately illustrated by the actual data for the 76 vehicles in the sample due to the suspect validity of the hours since oil change. To further illustrate the technique, a set of data was generated which fit the assumptions set forth when proposing this technique. Those assumptions were:

1. PPM levels may be related to the operating hours since oil change.

2. The wearmetal production process may be different for the normal and abnormal modes of operation.

3. The rate of wearmetal production is higher during failure than during normal operation

Thus simulated wearmetal data was generated by assuming:

$$Y(i) = B(0) + B(1)*X(i) + E(i)$$

Where the variables are defined as in chapter III.

Since the proposed technique approximating the regression line slope by the individual piecewise slopes was independent of the intercept term (i.e. B(0)), it was only necessary to derive estimates for B(1) and the variance of the error terms.

To determine a representative value to use for B(1), records for the 76 trucks were examined to determine whether any of the vehicles had wearmetal data for iron which exhibited the following characteristics:

1. Continuous, relatively uniform increases in hours since oil change data

2. No apparent gaps in the data

3. No abnormal drops in PPM levels without an accompanying record of oil change

4. At least 8 data points fitting the above requirements

A total of ten vehicles met the above criteria. The data from these vehicles was entered into the APL program REGRESS [Ref. 3], which fit a least squares linear regression line to the data. A plot of the residuals was examined to determine if there were any apparent violations of the assumption of normality. In addition, the R^2 values were examined to determine if there was a strong relationship between the dependent (PPM levels) and independent (hours since oil change) variables. Those samples which had R^2 values of .9 or greater and did not violate the subjective test for normality of residuals were chosen. A total of four vehicles met these criteria. The iron B(1) values for these vehicles are shown in Table III.

TABLE III
Regression Line Slopes

Vehicle number	B(1)
3903458	.3648
3818363	.4277
3850984	.5141
3903880	.3306

This technique is not meant to represent a statistically valid method for determining the behavior of the wearmetal data. It is meant only to provide a general idea of the magnitude of the wearmetal production rates.

The variance was assumed to be 1 for the sake of simplicity.

Thus to generate the data, all that was necessary was to determine the time at which the sample was to be taken, multiply it by the slope (B(1)) and add on an error term which was distributed N(0, 1). For illustrative purposes, times were generated at exact ten hour intervals (i.e. 10, 20, 30 etc. hours). The error terms were generated using the LLRANDOM II [Ref. 4] random number generating package. To simulate abnormal operations, data was generated which had a slope twice that of the normally operating equipment. Error terms were generated in the same manner as for the normally operating equipment. The data generated for the four pieces of equipment were combined and a frequency distribution (histogram) was formed through use of the FORTRAN program ANALGEN (Appendix F). Five hundred fifty 'normal' data elements and fifty 'abnormal' data elements were generated for each of the four values of B(1). The output frequency histogram is at Appendix E.

Upper quantiles of the distribution were determined as was done with the wearmetal levels. The quantiles found are in Table IV.

A problem may arise any time data from different equipment is grouped together. Unless the assumption that all equipment of the same type operate in the same manner is true, one could identify a measurement as abnormal in terms of the entire population when in fact it is within the

TABLE IV

Selected Quantiles of 10 Hour Wearmetal Production

	QUANTILE								
WEARMETAL	60th	70th	80th	90th	95th	96th	97th	98th	99th
Iron	4.69	5.22	5.84	6.97	8.18	8.83	9.46	10.14	10.81

normal operating range of the equipment from which the measurement was taken. To preclude this happening it would be preferable if guidelines could be generated for each equipment based on the operating history of that equipment alone. An example of the benefits of this method is shown using the generated data from vehicle 3903458.

Since the error terms generated were distributed Normal (0,1), the distribution of the PPM reading for each generated sample should have been Normal (10*B(1),2). This follows since the generated intervals were 10 hours therefore each 10 hour PPM reading would be 10 times the slope of the regression line (which was constant) plus the difference in the pairwise consecutive error terms. Since the mean of the error terms was 0, the mean of the PPM readings would be 0+10*B(1), while the variance would be the variance of B(1), which was zero, plus the variance of the difference in the error terms which was 2. Thus it would be expected that the frequency distribution for each generated sample would be a combination of two normal distributions offset from each other by 10 times the difference in their slopes (means). A histogram of the data generated from the B(1) value for vehicle 3903458 (Appendix E) shows this to be the case by the distinct bimodality of the distribution.

Thus if the assumptions of the wearmetal behavior during normal and abnormal operations hold, and the difference in wearmetal production rates during normal and abnormal operations is large in comparison to the variance in the sample of normal readings, then it should be quite apparent when a reading falls out of the range of normal variability.

V. CONCLUSIONS AND RECOMMENDATIONS

The determination of quantiles from the empirical distributions of wearmetal levels and of wearmetal trends was done to provide the director of the Ft. Ord Spectrometric Oil Analysis laboratory with general guidelines on what ranges of values he could expect for wearmetal levels and trends for the Continental LD/LDS/LDT 465/465-1 based on historical data for equipment supported by his laboratory. The presentation of results was different than that in TM 38-301-1 in that no attempt was made to attach labels (i.e. normal, marginal etc.) to these quantiles. This approach was taken to provide more flexibility and information with which to make subjective judgements on the condition of a piece of equipment since ultimately any recommendation made by an oil analysis laboratory is subjective based not only on published guidelines for a type of equipment, but also a knowledge of the operational history of the individual equipment in question.

The fact that operational history is an important factor in the recommendations made by the laboratory indicates the current practice of grouping all equipment of the same type together and applying general guidelines to the composite sample may not in fact be adequate for all individual pieces of equipment, being too conservative for equipment which normally produce wearmetal at a relatively high rate or too liberal for equipment which produce wearmetal at a relatively low rate. This problem is illustrated in Figure 5.1. In this figure, samples from two hypothetical pieces of equipment are shown. A regression analysis is performed on each sample individually giving regression lines 1 and 2

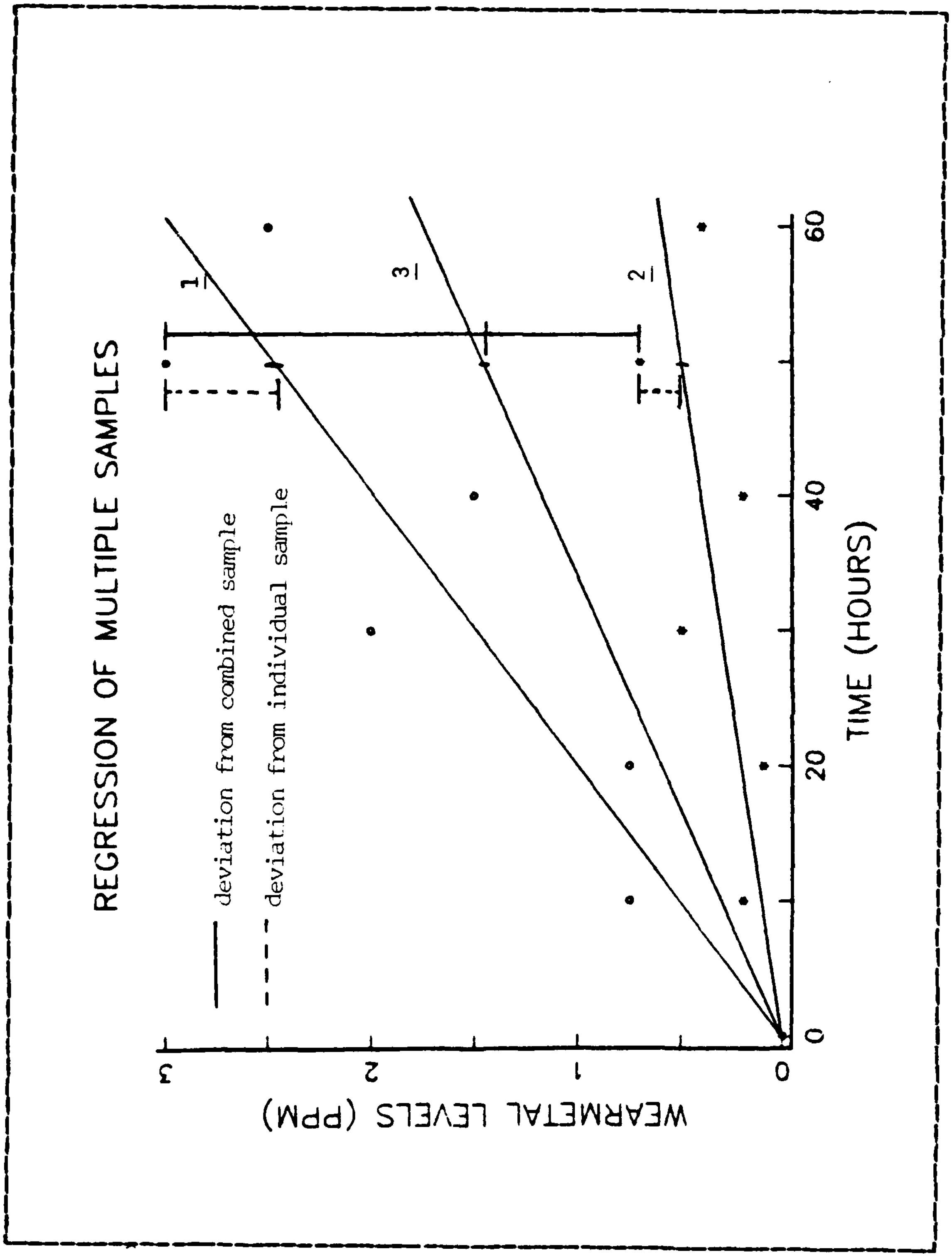


Figure 5.1 Regression of Combined Samples.

respectively. These lines are constructed to minimize the sum of the squared deviations of each sample point from the line. Unless the two regression lines are collinear (an extremely unlikely situation), a regression analysis performed on the combined data would result in a regression line (line 3) which, while being the best fit for the combined data, would have a larger residual sum of squares than either of the individual sample regression lines indicating the fit of the regression line for the combined data was not as good a fit as that of the individual samples. Additionally, the combined regression line would overestimate the wearmetal production rate of engine 2 and underestimate the wearmetal production rate of engine 1. Thus a guideline based on the combined samples might fail to identify an impending failure in engine 2 or erroneously signal an impending failure in engine 1.

This same problem applies to the methodology proposed of estimating the regression line by the individual 10 hour trend readings. While each 10 hour trend reading could be considered a fairly good estimate of the slope of the regression line for that individual piece of equipment, it would likely be a poor estimate of the slope of the regression line obtained by combining the data from all pieces of equipment of the same model. Again, the wearmetal production characteristics of the individual equipment would be masked by the combined characteristics of the other pieces of equipment.

While developing individual guidelines on each piece of equipment is much more complicated than setting general guidelines for all equipment of the same type, these individual guidelines would allow the laboratory director to make a much more accurate recommendation after analyzing an oil sample.

Implementation of this methodology at the laboratory level would require computational capability (i.e. a computer). Since the distribution of the 10 hour PPM trends for an individual piece of equipment is expected to be normal, any desired quantiles of the distribution could be derived from the sample mean and standard deviation and the standard normal tables. As additional data elements were added (as a result of additional samples) these statistics would provide an increasingly better estimation of the true wearmetal trend characteristics of the individual equipment.

The goodness of any predictive methodology is related to the quality of the data on which the prediction is made. Thus to derive the maximum benefits from the oil analysis program, additional emphasis must be placed on the proper collecting of oil samples and reporting of equipment operating data. This will require not only increased command emphasis, but convincing maintenance personnel of the benefits of the program in reduced maintenance expense, increased readiness and greater safety.

APPENDIX A

TYPE VEHICLES USING THE CONTINENTAL LD/LDS/LDT-465 ENGINE

END ITEM	NOMENCLATURE
M34A2	2 1/2 Ton Cargo Truck
M35A2	" "
M35A2C	" "
M36A2	" "
M45A2	2 1/2 Ton Bolster, truck
M46A2	2 1/2 Ton truck chassis
M49A2C	2 1/2 Ton Tank truck, fuel
M50A2	2 1/2 Ton Tank truck, H2O
M50A3	2 1/2 Ton Tank truck, H2O
M51A2	5 Ton Dump truck
M52A2	5 Ton Tractor truck
M54A2	5 Ton Cargo truck
M54A2C	" "
M55A2	" "
M61A2	5 Ton truck chassis
M63A2	" "
M109A3T	2 1/2 Ton truck, tractor, wrecker
M185A3	Inst Repair truck
M246A2	5 Ton truck, tractor, wrecker

M275A2	2 1/2 Ton Tractor, truck
M291A2	5 Ton truck, Exp van
M292A2	2 1/2 Ton truck, Exp van
M292A5	" "
M342A2	2 1/2 Ton Dump truck

APPENDIX B

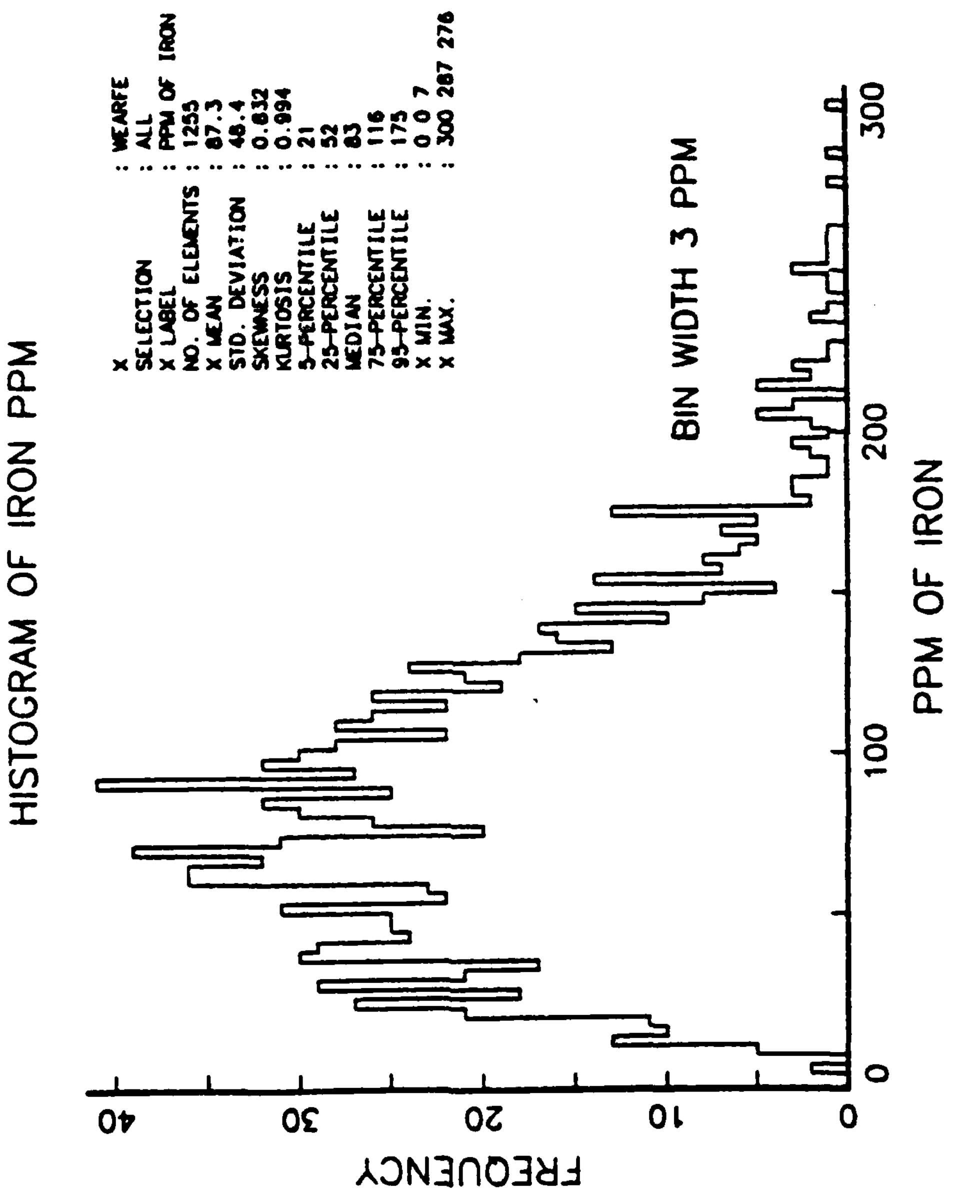
LIST OF SERIAL NUMBERS OF ENGINES STUDIED

25880A	3817608	2811
12688	3929002	31244
3903358	3923271	3903782
3923514	3901901	3902143
3929006	3920268	3921134
3914728	3921828	3923959
3901793	3901793	13778
3902619	20279	6905
3765142	3806178	382045
3922795	3903772	38176592
3827828	10305783	980716
3891139	26197	3818461
3862237	3903451	880819
391707	3901904	3902362
3902420	3903137	24165
3924675	3924712	3902430
30908	3901455	79168
3903418	3922157	75145
39238457	3912945	3914805
3925101	3903884	3047329
3903458	3939020	3818363
3901270	3903993	3900086
8805274	4076463	3925768
3850984	3903880	3903421
3903212	3816622	3929195
3903350		

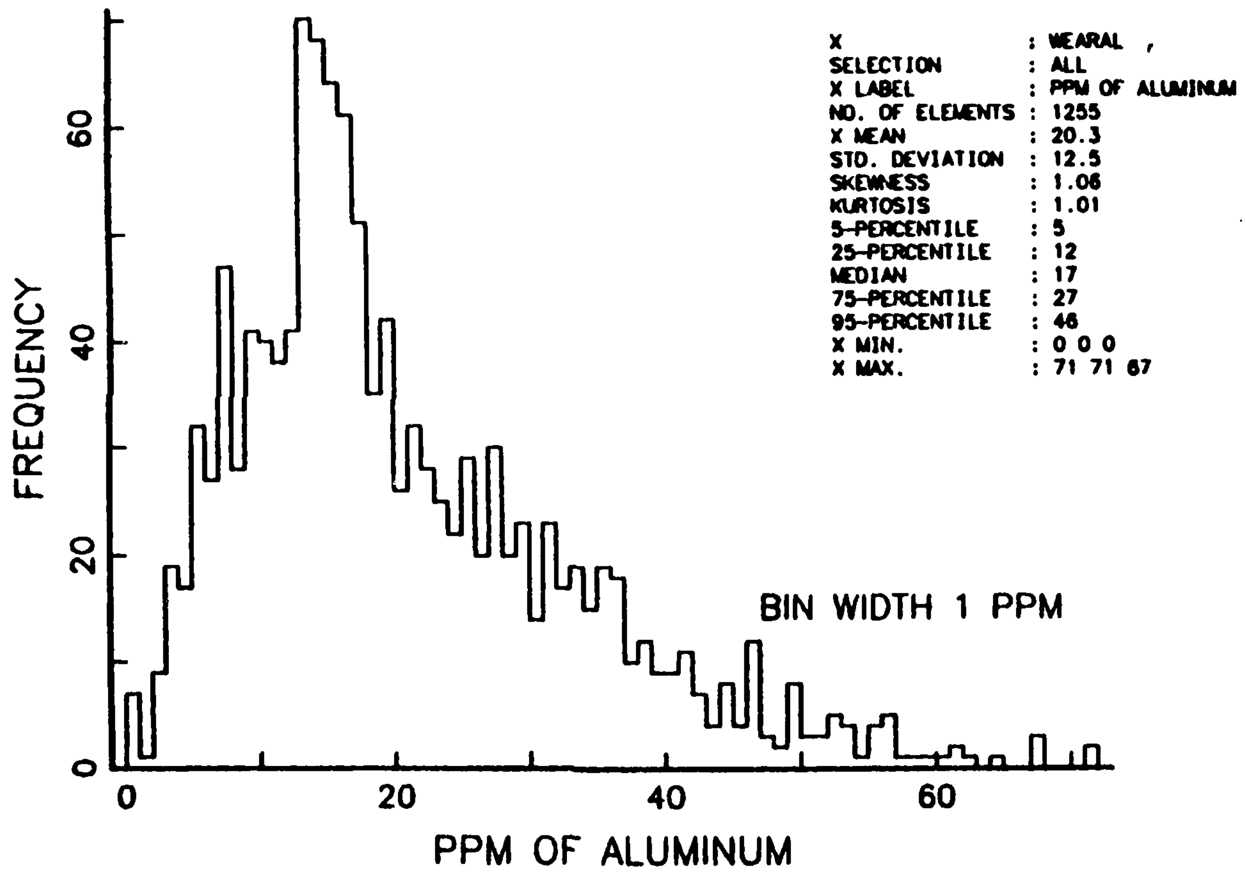
APPENDIX C

FREQUENCY HISTOGRAMS FOR WEARMETAL LEVELS

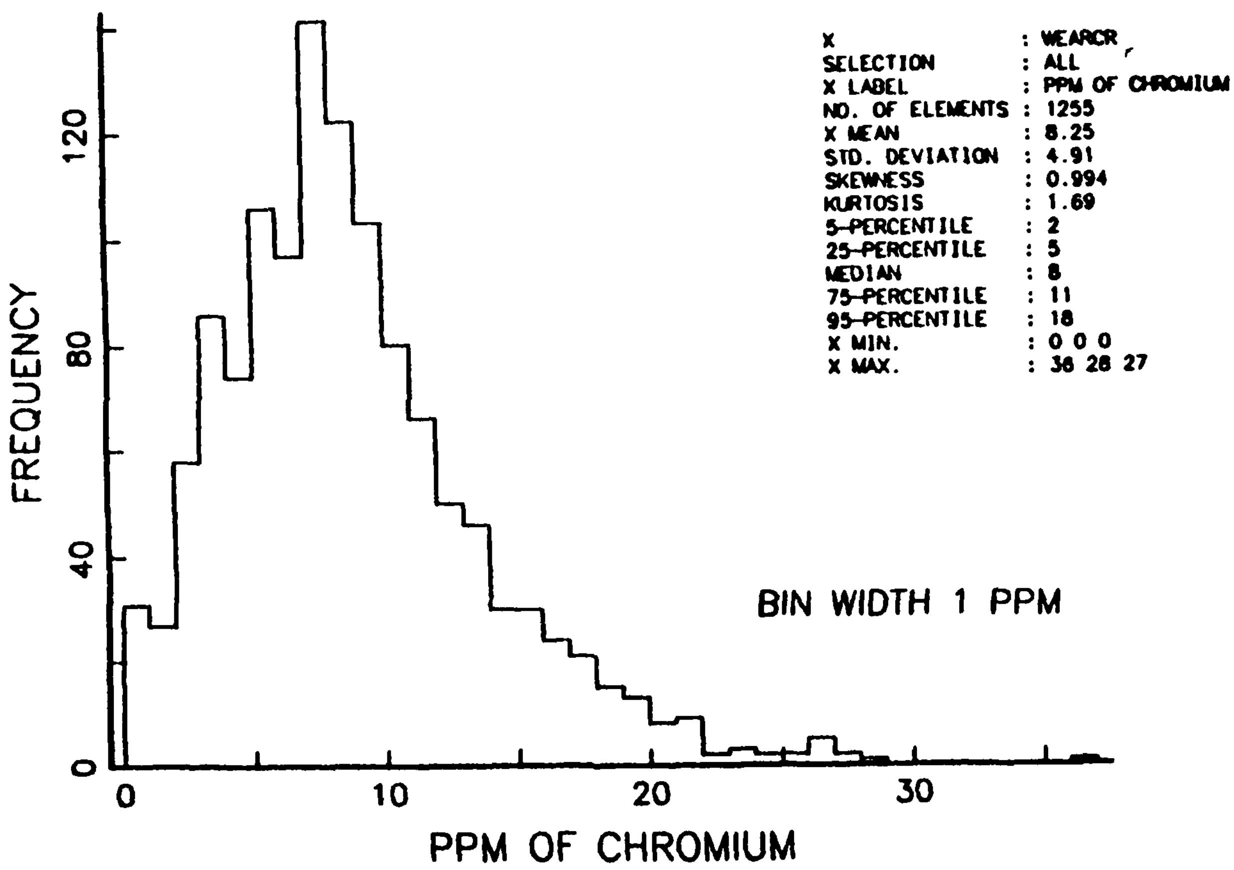
This appendix contains histograms of the historical wearmetal level data for the sample of engines studied.



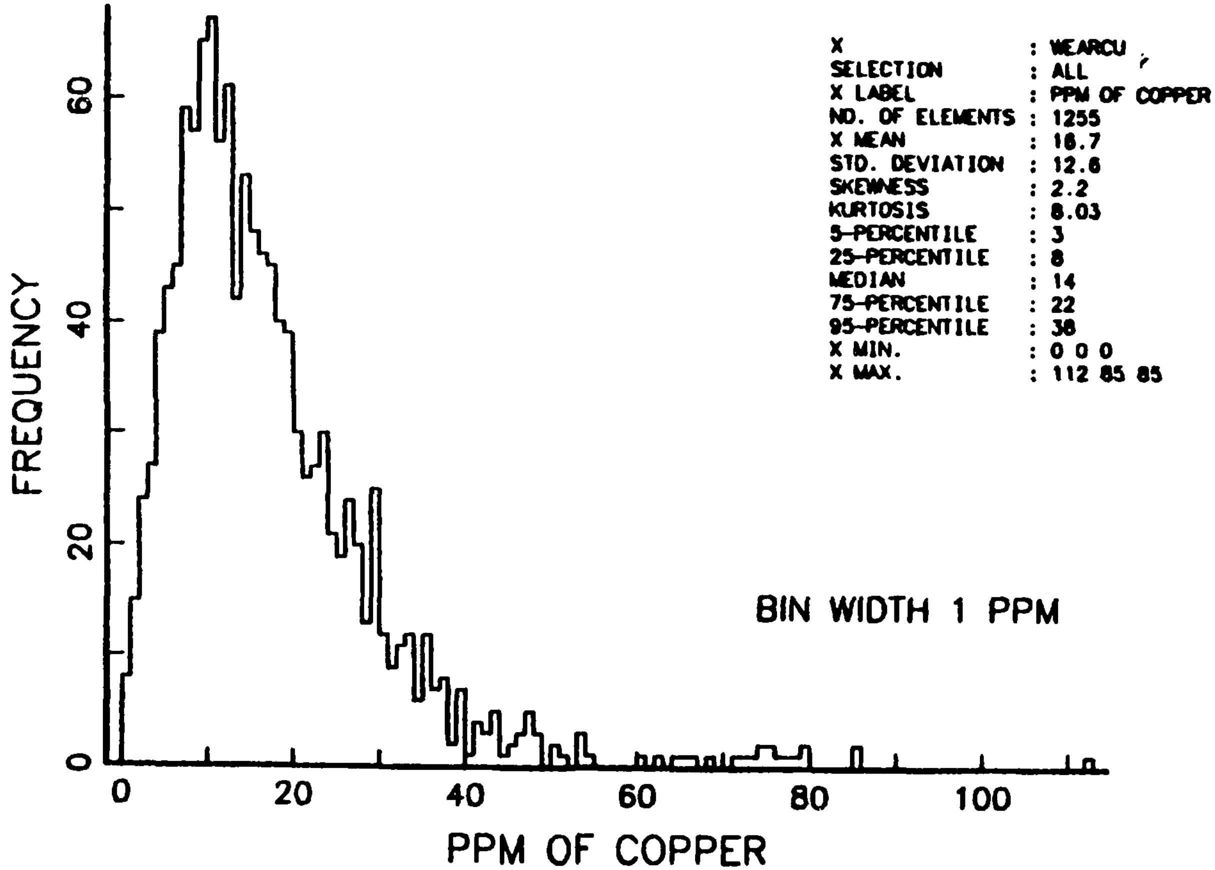
HISTOGRAM OF ALUMINUM PPM

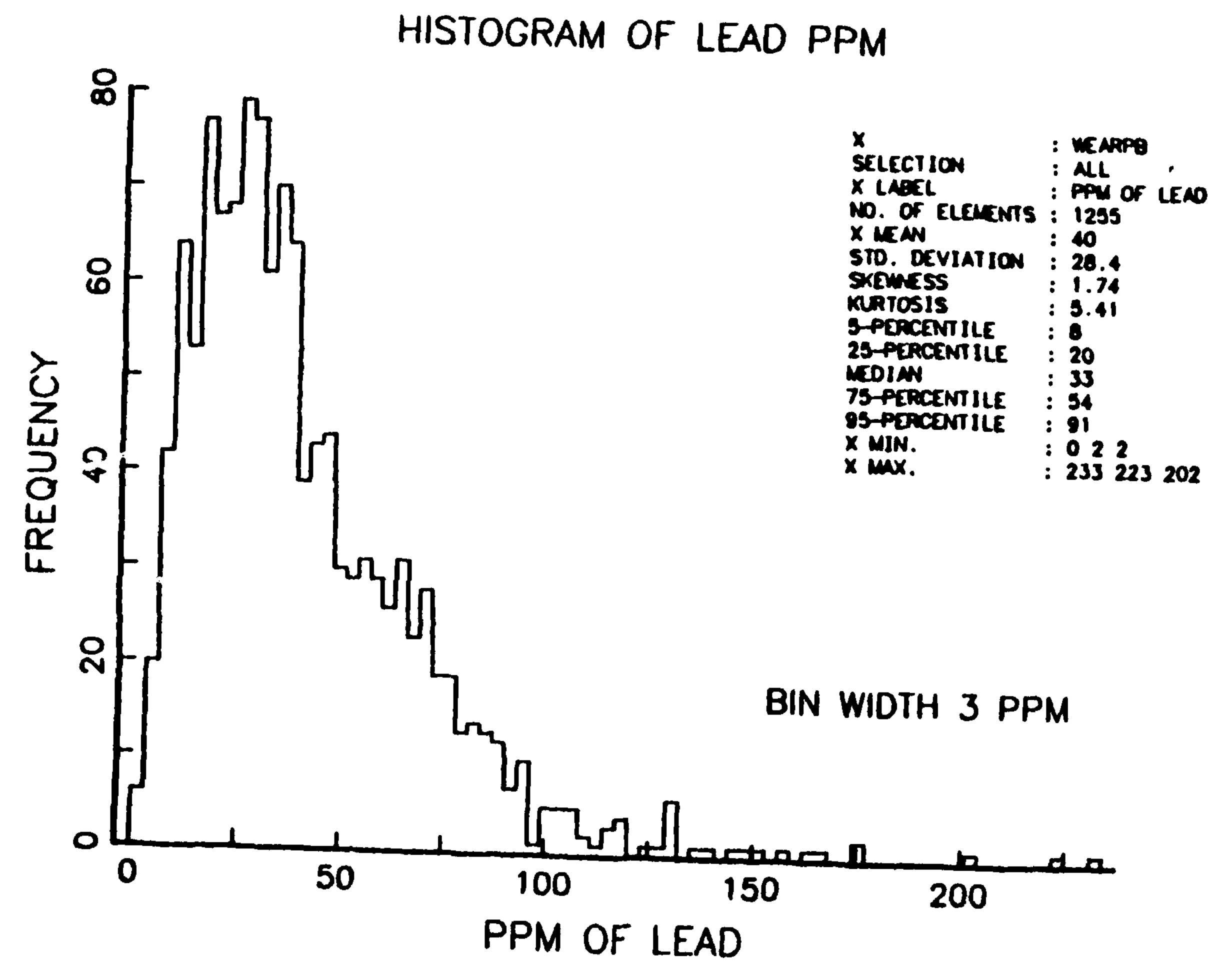


HISTOGRAM OF CHROMIUM PPM



HISTOGRAM OF COPPER PPM




HISTOGRAM OF LEAD PPM
FREQUENCY
0
20
40
60
80
0
50
100
150
200
PPM OF LEAD
BIN WIDTH 3 PPM
X : WEARPB
SELECTION : ALL
X LABEL : PPM OF LEAD
NO. OF ELEMENTS : 1255
X MEAN : 40
STD. DEVIATION : 28.4
SKEWNESS : 1.74
KURTOSIS : 5.41
5-PERCENTILE : 8
25-PERCENTILE : 20
MEDIAN : 33
75-PERCENTILE : 54
95-PERCENTILE : 91
X MIN. : 0 2 2
X MAX. : 233 223 202

APPENDIX D
OUTPUT FOR TREND ANALYSIS

The results of this portion of the analysis were highly variable. The existance of a few very large and very small values prevented the display of the bulk of the results in detail. To expand on the display of the non-extreme results, the 10 largest and 10 smallest values were truncated prior to producing the histograms. The values truncated for each wearmetal are listed in Table V.

TABLE V

Truncated Wearmetal Trend Values

IRON LOW	IRON HIGH	ALUMINUM LOW	ALUMINUM HIGH	CHROMIUM LOW	CHROMIUM HIGH
-680	223.33	-280	64	-70	22.22
-450	230	-190	70	-20	23.33
-370	230	-60	70	-12.31	27.5
-135.71	232	-40	70	-10	30
-125.83	250	-30	75.71	-10	40
-100	263.33	-30	110	-10	40
-100	270	-28.57	110	-10	50
-92.5	383.33	-25	130	-10	50
-86.67	610	-23.33	130	-10	53.33
-80	915	-22.5	355	-6.67	70

COPPER LOW	COPPER HIGH	LEAD LOW	LEAD HIGH
-100	45.46	-380	103.33
-50	46	-260	110
-30	50	-251.43	115
-21.43	62.5	-120	117
-19.23	70	-90	126.67
-18.33	80	-83.33	130
-12.67	83.33	-80	250
-12.5	110	-60	252.86
-12.5	160	-56.67	275
-11.52	180	-40	380

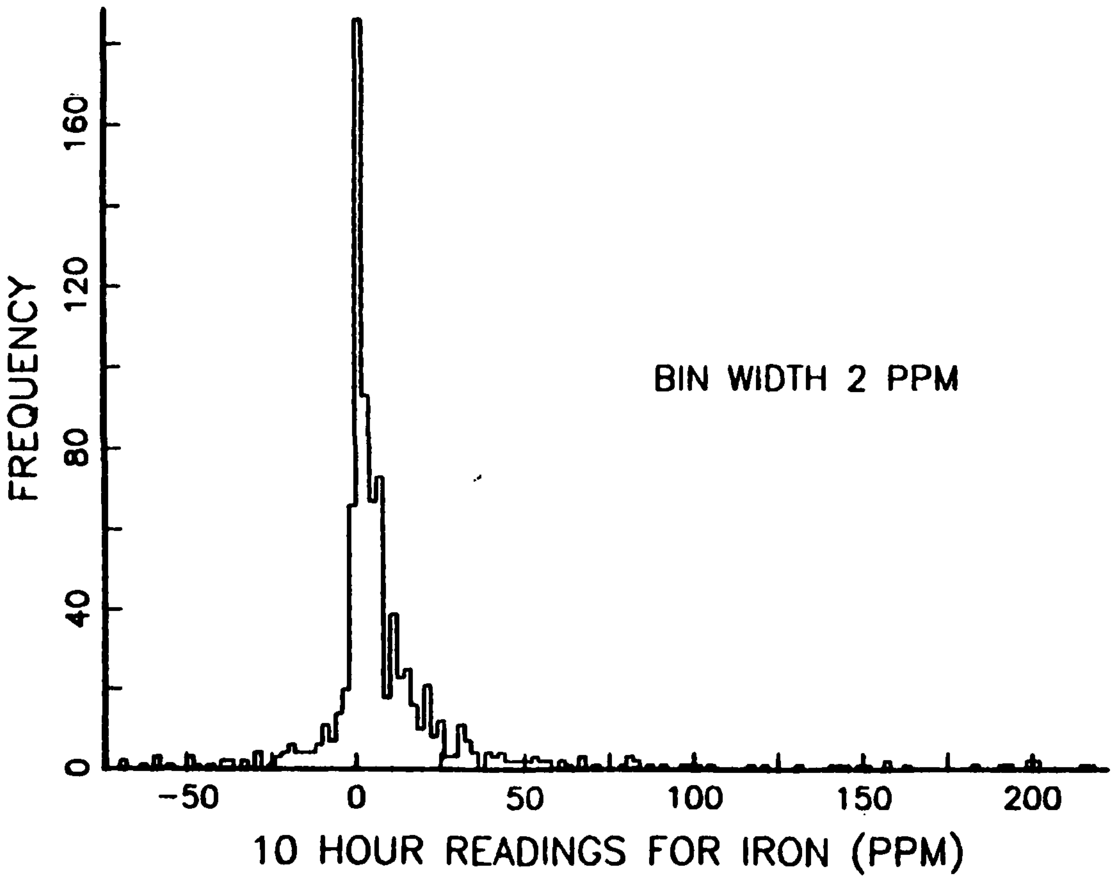
Selected statistics on the 10 hour trends are shown in Table VI.

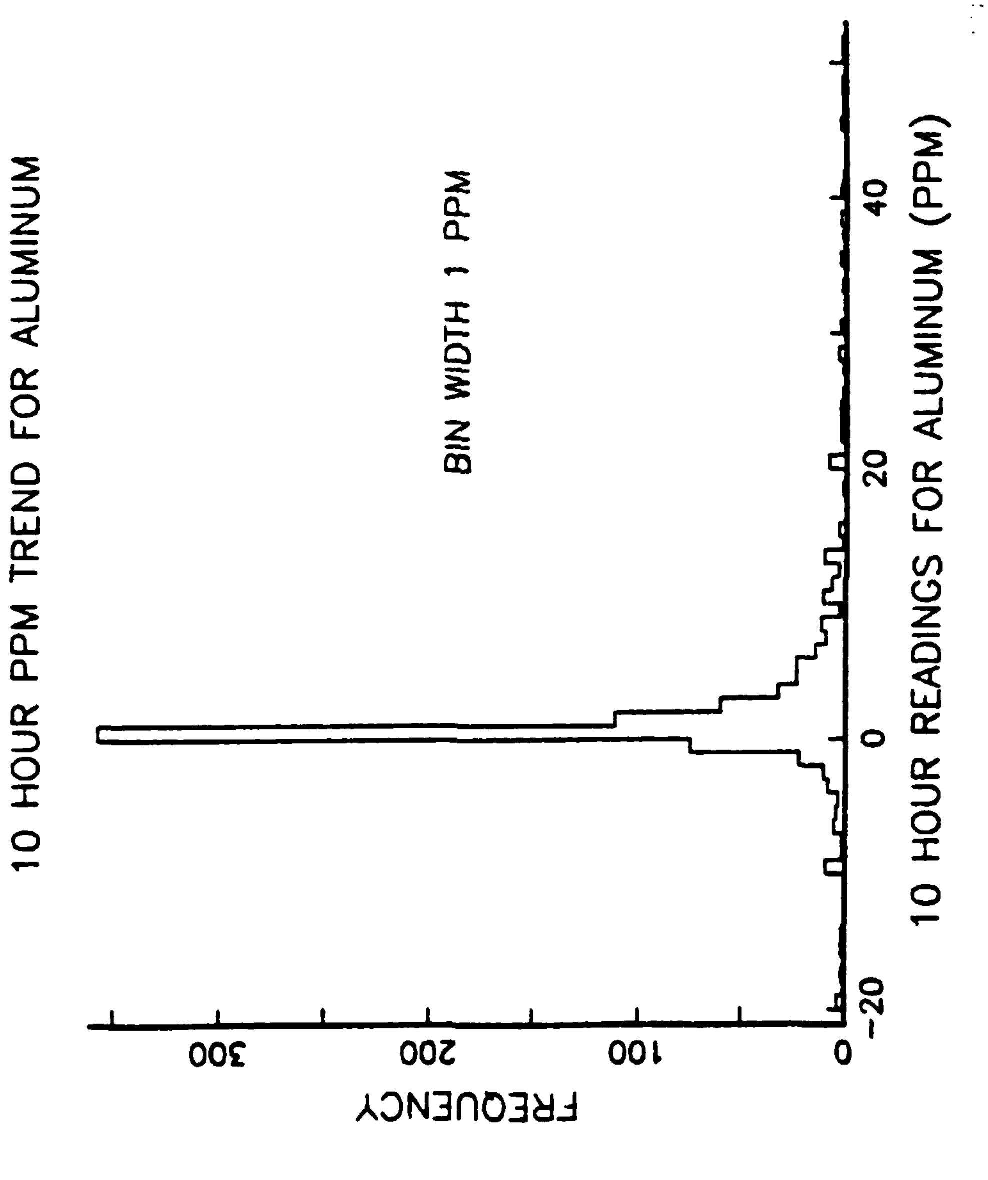
TABLE VI

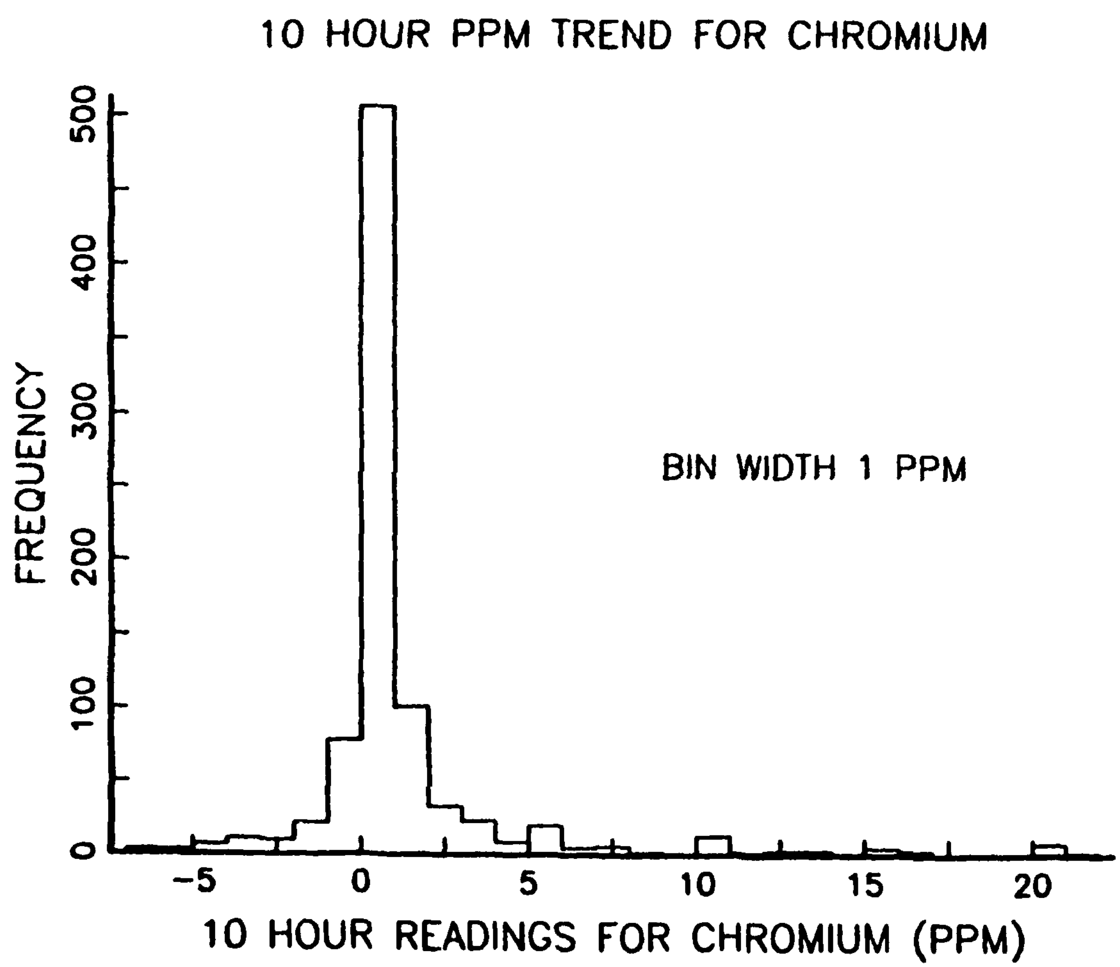
Trend Statistics

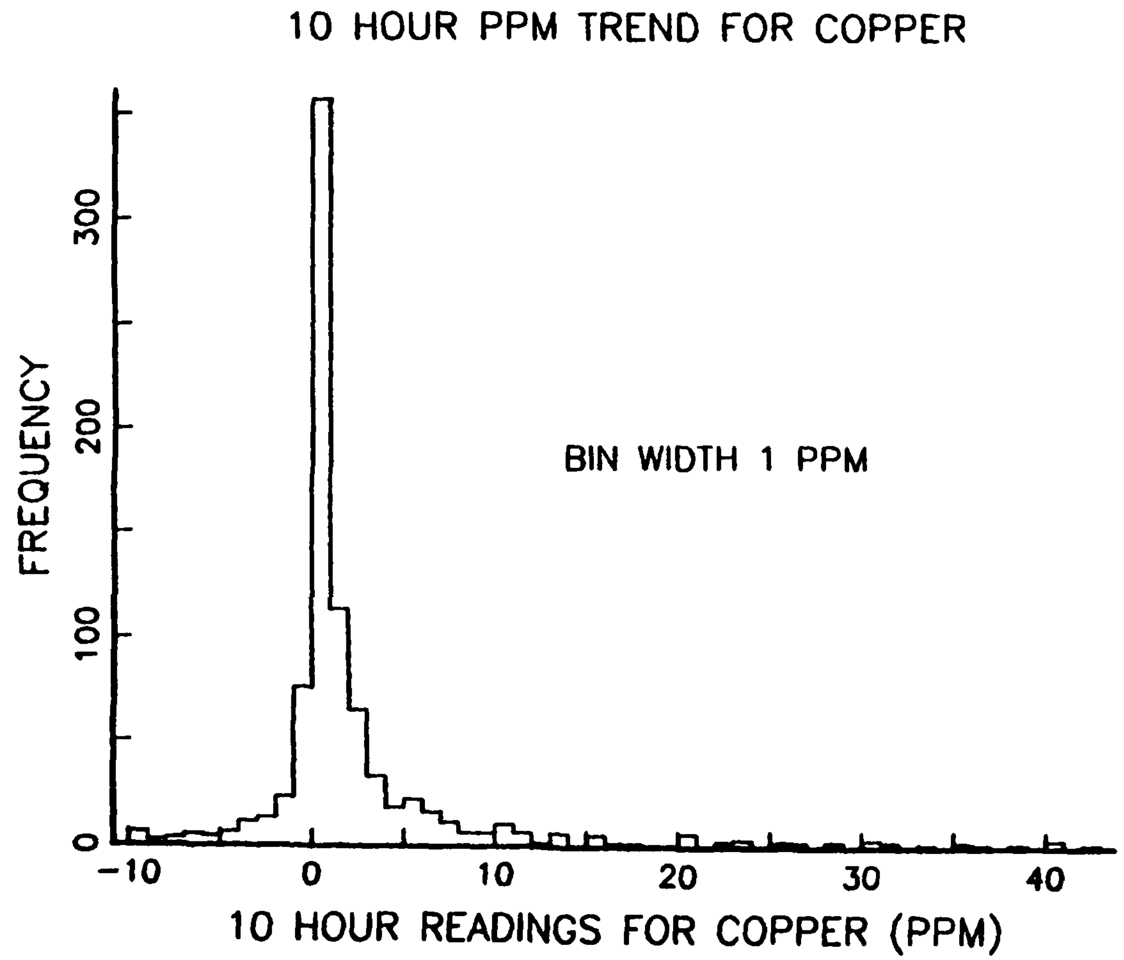
	WEARMETAL				
STATISTIC	Iron	Alum	Chrom	Copp	Lead
MEANS	11.88	3.08	2.97	1.32	5.60
STD.DEV	62.69	20.81	12.86	6.11	32.54
L. QRTIS	0.13	0.00	0.00	0.00	0.00
MEDIANS	3.49	0.71	0.61	0.23	1.37
U. QRTIS	11.76	2.58	2.44	1.11	6.19

10 HOUR PPM TREND FOR IRON

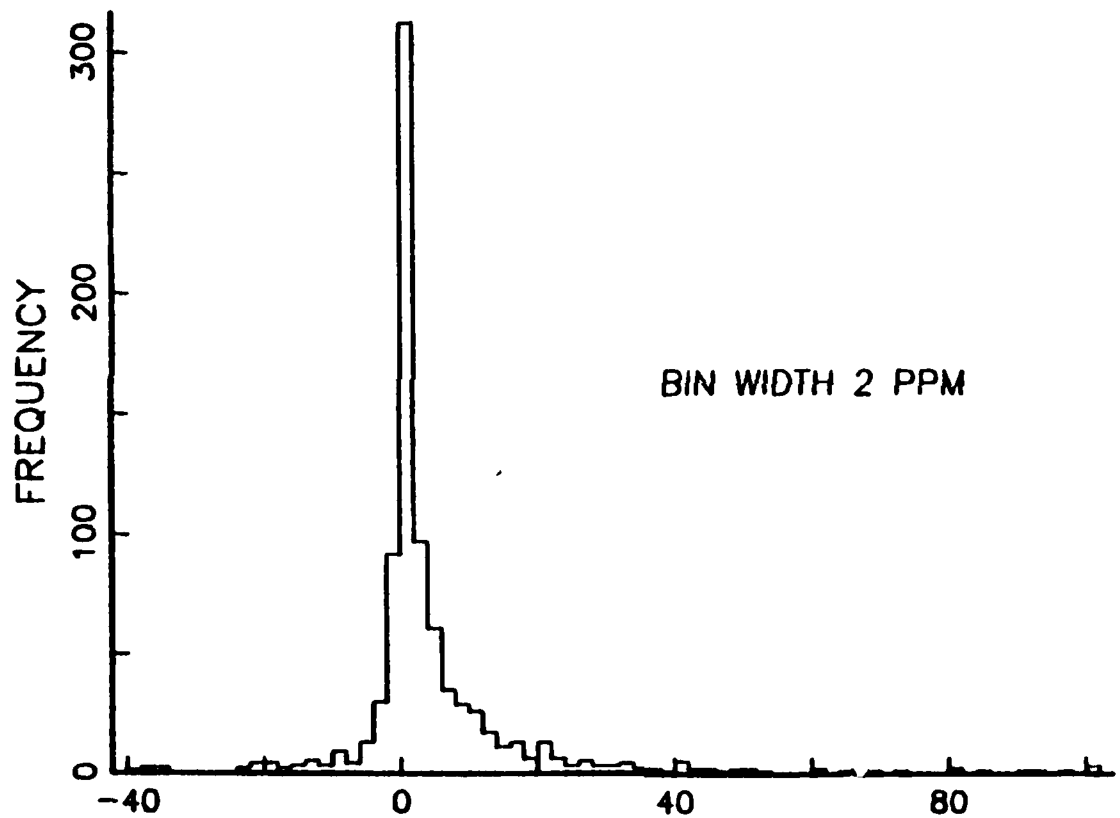



10 HOUR PPM TREND FOR ALUMINUM
BIN WIDTH 1 PPM
FREQUENCY
0
100
200
300
−20
0
20
40
10 HOUR READINGS FOR ALUMINUM (PPM)


10 HOUR PPM TREND FOR CHROMIUM
FREQUENCY
0
100
200
300
400
500
BIN WIDTH 1 PPM
-5
0
5
10
15
20
10 HOUR READINGS FOR CHROMIUM (PPM)


10 HOUR PPM TREND FOR COPPER
FREQUENCY
0
100
200
300
BIN WIDTH 1 PPM
-10
0
10
20
30
40
10 HOUR READINGS FOR COPPER (PPM)

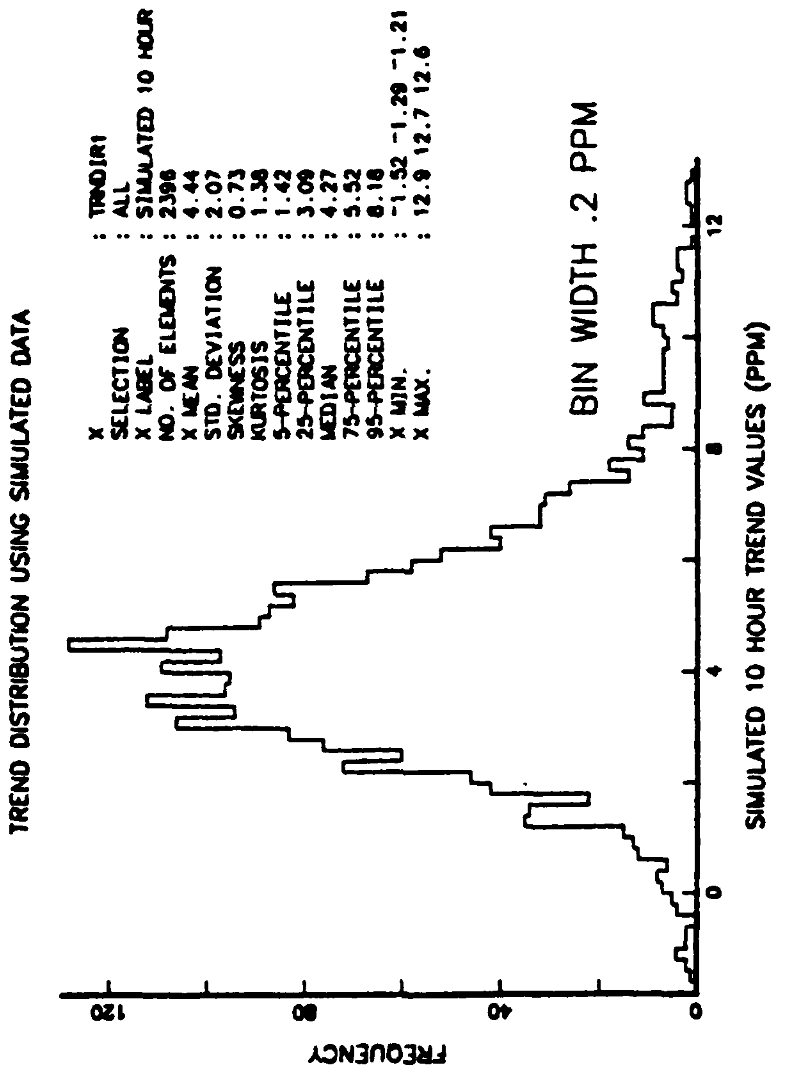
10 HOUR PPM TREND FOR LEAD



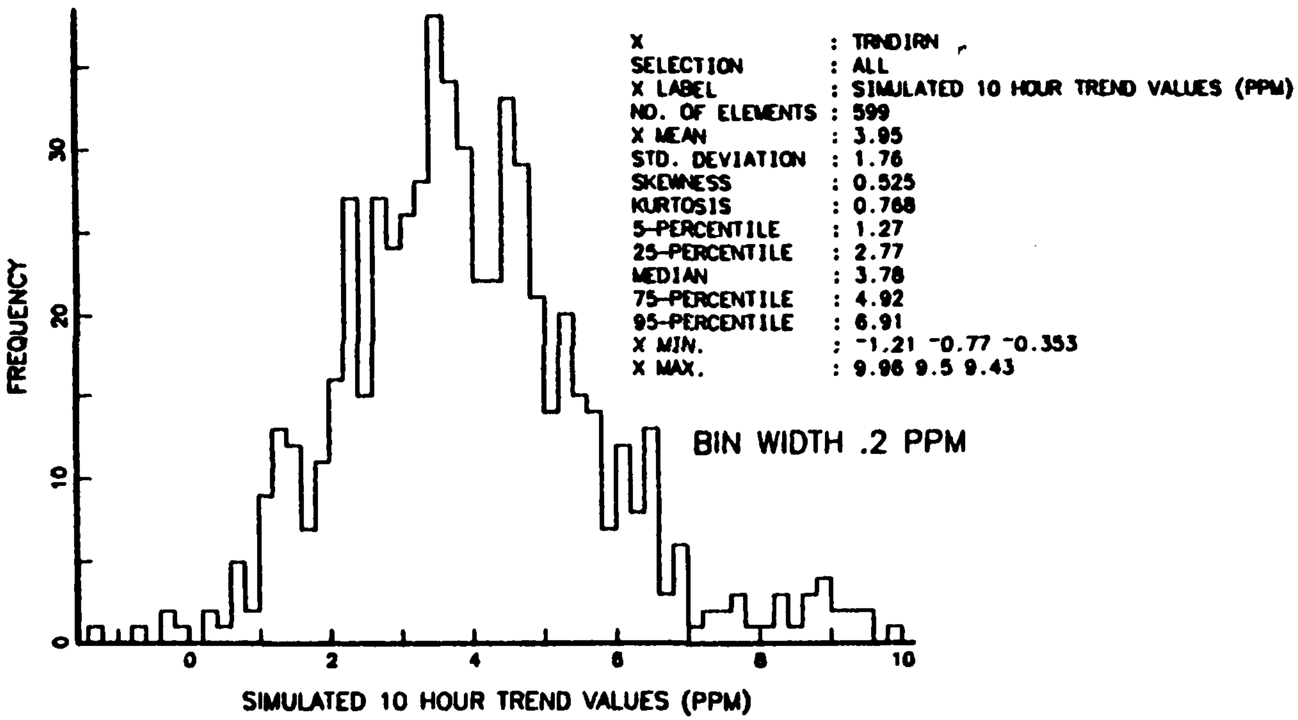
APPENDIX E

OUTPUT FOR TREND ANALYSIS USING SIMULATED DATA

This appendix contains histograms of the wearmetal trend analysis for the simulated wearmetal data. The first histogram is for the combined data of four engines while the second is a histogram for an individual engine.



SINGLE VEHICLE TREND USING SIMULATED DATA



APPENDIX F

COMPUTER PROGRAMS

```
C **** PROGRAM WEARMTL****
C PROGRAM READS IN WEARMETAL LEVELS FOR DIFFERENT
C EQUIPMENT AND PLOTS FREQUENCY HISTOGRAMS
C RICHARD F. BAUER 11 APR 1983
      REAL HR(1260),FE(1260),AL(1260),CR(1260),CU(1260),
     *PB(1260),INDX(1260)
      INTEGER I,J
      DIMENSION NAME (200)
      J=0
      I=0
      DO 15 J=1,75
           READ (5,100) NAME(J)
C          WRITE (6,270) NAME(J)
C READ IN THE WEARMETAL DATA
  10  CONTINUE
      I=I+1
      READ(5,110) HR(I),FE(I),AL(I),CR(I),CU(I),PB(I)
C     WRITE(6,250) HR(I),FE(I),AL(I),CR(I),CU(I),PB(I)
      INDX(I)=J
      IF ((HR(I)).GT.-99) GO TO 10
           I=I-1
 15   CONTINUE
C WRITE WEARMETAL LEVELS TO APL DATA FILE
C     WRITE (10,*) PB
C     WRITE (9,*) CU
C     WRITE (8,*) CR
C     WRITE (7,*) AL
C     WRITE (11,*) FE
C GENERATE HISTOGRAMS OF WEARMETAL LEVELS
      CALL HISTGP (FE,I,15)
      WRITE (6,200)
      CALL HISTGP (AL,I,15)
      WRITE (6,210)
      CALL HISTGP (CR,I,15)
      WRITE (6,220)
      CALL HISTGP (CU,I,15)
      WRITE (6,230)
      CALL HISTGP (PB,I,15)
C     WRITE (6,240)
      WRITE (11,*) FE
C     WRITE (7,*) AL
C     WRITE (8,*) CR
C     WRITE (9,*) CU
C     WRITE (10,*) PB
      STOP
 100  FORMAT (A10)
 110  FORMAT (6F10.1)
 200  FORMAT (1X,'HISTOGRAM OF PPM LEVELS FOR IRON')
 210  FORMAT (1X,'HISTOGRAM OF PPM LEVELS FOR ALUMINUM')
 220  FORMAT (1X,'HISTOGRAM OF PPM LEVELS FOR CHROMIUM')
 230  FORMAT (1X,'HISTOGRAM OF PPM LEVELS FOR COPPER')
 240  FORMAT (1X,'HISTOGRAM OF PPM LEVELS FOR LEAD')
 245  FORMAT (1X,5F10.5)
C250  FORMAT (1X,6F10.1)
C270  FORMAT (1X,A10)
      END
```

```
C ***** PROGRAM ANALYSIS*******
C PROGRAM ANALYZES THE 10 HOUR TRENDS IN WEARMETAL
C RICHARD F. BAUER
      REAL DELHR(1400),DELFE(1400),DELAL(1400),
     *DELCR(1400),DELCU(1400),DELPB(1400),
     *TRNDAL(1400),TRNDCR(1400),TRNDPB(1400),
     *HR(1400),FE(1400),AL(1400),CR(1400),
     *PB(1400),CU(1400),TRNDCU(1400),TRNDFE(1400)
      INTEGER PRE
      DIMENSION NAME(75)
              I=1
              K=1
      DO 50 J=1,75
      READ (5,110) NAME (J)
      WRITE (6,111) NAME(J)
  5   CONTINUE
              READ (5,100) HR(I),FE(I),AL(I),CR(I),CU(I),PB(I)
C             WRITE (6,200) HR(I),FE(I),AL(I),CR(I),CU(I),
     *PB(I)
              IF (HR(I).EQ.(0.)) GO TO 5
  6   CONTINUE
              I=I+1
  7   CONTINUE
              READ (5,100) HR(I),FE(I),AL(I),CR(I),CU(I),PB(I)
C             WRITE (6,200) HR(I),FE(I),AL(I),CR(I),CU(I),
     *PB(I)
              IF (HR(I).EQ.-99.) GO TO 49
              PRE=I-1
              IF (HR(I).EQ.(0.)) GO TO 7
              IF (HR(I).LE.HR(PRE)) GO TO 10
                   DELHR(K)=HR(I)-HR(PRE)
                   DELFE(K)=FE(I)-FE(PRE)
                   DELAL(K)=AL(I)-AL(PRE)
                   DELCR(K)=CR(I)-CR(PRE)
                   DELCU(K)=CU(I)-CU(PRE)
                   DELPB(K)=PB(I)-PB(PRE)
C     WRITE (6,*) DELHR(K),DELFE(K),DELAL(K),DELCR(K),
C    *DELCU(K),DELPB(K)
                   GO TO 15
 10           CONTINUE
              DELHR(K)=HR(I)
              DELFE(K)=FE(I)
              DELAL(K)=AL(I)
              DELCR(K)=CR(I)
              DELCU(K)=CU(I)
              DELPB(K)=PB(I)
C             WRITE (6,*) DELHR(K),DELFE(K),DELAL(K),DELCR(K),
C    *DELCU(K),DELPB(K)
 15   CONTINUE
      TRNDFE(K)=(DELFE(K)/DELHR(K))*10.
      TRNDAL(K)=(DELAL(K)/DELHR(K))*10.
      TRNDCR(K)=(DELCR(K)/DELHR(K))*10.
      TRNDCU(K)=(DELCU(K)/DELHR(K))*10.
      TRNDPB(K)=(DELPB(K)/DELHR(K))*10.
C     WRITE (6,*) TRNDFE(K),TRNDAL(K),TRNDCR(K),TRNDCU(K),
     *TRNDPB(K)
      K=K+1
      GO TO 6
 49   CONTINUE
      I=I-1
 50   CONTINUE
      CALL HISTGP (TRNDFE,K,0)
      WRITE (6,210)
      CALL HISTGP (TRNDAL,K,0)
      WRITE (6,220)
      CALL HISTGP (TRNDCR,K,0)
      WRITE (6,230)
      CALL HISTGP (TRNDCU,K,0)
      WRITE (6,240)
```

```
      CALL HISTGP (TRNDPB,K,0)
      WRITE (6,250)
C     WRITE (6,210)
C     WRITE (11,*) TRNDFE
C     WRITE (6,220)
C     WRITE (7,*) TRNDAL
C     WRITE (6,230)
C     WRITE (8,*) TRNDCR
C     WRITE (6,240)
C     WRITE (9,*) TRNDCU
C     WRITE (6,250)
C     WRITE (10,*) TRNDPB
      STOP
  100 FORMAT (1X,6F10.5)
  110 FORMAT (1X,A10)
  111 FORMAT (1X,A10)
C200 FORMAT (1X,6F10.2)
  210 FORMAT (1X,'HISTOGRAMS OF PIECEWISE TRENDS FOR
     *IRON' )
  220 FORMAT (1X,'HISTOGRAMS OF PIECEWISE TRENDS FOR
     *ALUMINUM')
  230 FORMAT (1X,'HISTOGRAMS OF PIECEWISE TRENDS FOR
     *COPPER')
  240 FORMAT (1X,'HISTOGRAMS OF PIECEWISE TRENDS FOR
     *CHROMIUM')
  250 FORMAT (1X,'HISTOGRAMS OF PIECEWISE TRENDS FOR
     *LEAD')
      END
```

```
C ***** PROGRAM ANALGEN *******
C PROGRAM TO GENERATE SIMULATED DATA FOR USE IN ANALYSIS
C RICHARD F. BAUER
      REAL HR(600),IRON(600),ERROR(2400),DELHR(599),
     *DELIRN(599),TRDIRN(599),IRON1(2400),
     *DELIR1(2396),TRDIR1(2396)
      INTEGER PRE,PREI,PREJ,PREK,PREL
      SEED=10.
      CALL LNORM(SEED,ERROR,2400,2,0)
      DO 5 I=1,550
           HR(I)=10.*(FLOAT(I))
           IRON(I)=((.3648)*HR(I))+ERROR(I)
           J=I+600
           K=I+1200
           L=I+1800
           IRON1(I)=((.3648)*HR(I))+ERROR(I)
           IRON1(J)=((.4277)*HR(I))+ERROR(J)
           IRON1(K)=((.5141)*HR(I))+ERROR(K)
           IRON1(L)=((.3306)*HR(I))+ERROR(L)
    5 CONTINUE
      B0=IRON(I)
      B0I=IRON1(I)
      B0J=IRON1(J)
      B0K=IRON1(K)
      B0L=IRON1(L)
      DO 7 I=551,600
           JJ=I-500
           HR(I)=10.*(FLOAT(JJ))
           J=I+600
           K=I+1200
           L=I+1800
           IRON(I)=B0+((.7296)*HR(I))+ERROR(I)
           IRON1(I)=B0I+((.7296)*HR(I))+ERROR(I)
           IRON1(J)=B0J+((.9554)*HR(I))+ERROR(J)
           IRON1(K)=B0K+((1.0282)*HR(I))+ERROR(K)
           IRON1(L)=B0L+((.6612)*HR(I))+ERROR(L)
    7 CONTINUE
      DO 10 JJ=2,600
           I=JJ
           J=JJ+600
           K=JJ+1200
           L=JJ+1800
           PRE=JJ-1
           DELHR(JJ)=HR(JJ)-HR(PRE)
           DELIRN(JJ)=IRON(JJ)-IRON(PRE)
           TRDIRN(JJ)=(DELIRN(JJ)/DELHR(JJ))*10.
           PREI=I-1
           PREJ=J-1
           PREK=K-1
           PREL=L-1
           DELIR1(I)=IRON1(I)-IRON1(PREI)
           DELIR1(J)=IRON1(J)-IRON1(PREJ)
           DELIR1(K)=IRON1(K)-IRON1(PREK)
           DELIR1(L)=IRON1(L)-IRON1(PREL)
           TRDIR1(I)=(DELIR1(I)/DELHR(JJ))*10.
           TRDIR1(J)=(DELIR1(J)/DELHR(JJ))*10.
           TRDIR1(K)=(DELIR1(K)/DELHR(JJ))*10.
           TRDIR1(L)=(DELIR1(L)/DELHR(JJ))*10.
C          WRITE (6,200) TRDIRN(JJ)
  10    CONTINUE
      CALL HISTGP (TRDIRN,PRE,15)
      WRITE (4,*) TRDIRN
      CALL HISTGP (TRDIR1,2396,15)
      STOP
C200  FORMAT (1X,1F10.5)
      END
```

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